

Physics of mirror photons

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Abstract

The physics of kinetic mixing between ordinary and mirror photons is elucidated. An important role is played by four linear combinations we dub the physical photon, the sterile photon, the physical mirror photon, and the sterile mirror photon. Because of the mass degeneracy between the two gauge bosons, quantum coherence effects are important. The physical photon becomes a certain coherent superposition of the bare ordinary photon and the bare mirror photon. Similarly, the physical mirror photon is another, but *not orthogonal*, coherent superposition. Using a Bloch equation analysis, we show that the physical mirror photon decoheres into a mixture of the physical (ordinary) photon and the sterile photon when it propagates through ordinary matter. Observational signatures for some hybrid ordinary/mirror binary astrophysical systems are qualitatively discussed, and speculative connections with as yet mysterious observed objects are made. In particular, we speculate that the recently reported halo white dwarfs might actually be mirror halo stars.

I. INTRODUCTION

There has been considerable interest in the study of particle physics implications of the atmospheric [1], solar [2], LSND [3] and other neutrino experiments. The main purpose of such investigations has been to understand what theories could be responsible for the observed experimental features, which in the atmospheric and solar cases give strong evidence for large angle neutrino oscillations. One of these theories is the Exact Parity Model (EPM) (also known as the Mirror Matter Model) which introduces parity or “mirror” partners for all ordinary particles (except the graviton) and thus restores the parity invariance apparently broken by the weak interactions [4–6]. The EPM predicts pairwise maximal mixing between ordinary and mirror neutrinos and provides a basis for an explanation of the atmo-

spheric and solar neutrino data [7]. This explanation does not require large mixing between generations and is also consistent with the LSND experiment.¹

Another interesting implication of this idea is that the mirror nucleons/atoms provide a natural candidate for dark matter [5,9,10]. This hypothesis can nicely explain some of the features of dark matter. For example, the heavy MACHO objects inferred to exist in the halo of our galaxy by the microlensing experiments [11] can be naturally interpreted as mirror stars [10]. If the dark matter is composed of mirror matter then it is also possible that some mirror matter exists in our solar system and in other solar systems. In fact a mirror planet could form very close to an ordinary star and may provide a possible explanation for the close-in extra-solar planets discovered around nearby stars [12]. For other possible astrophysical, cosmological and geophysical implications of mirror matter see Ref. [13].

Ordinary and mirror matter interacts through gravitation, and through the mixing of colourless and neutral particles with their mirror partners [6,7,14,15]: neutrinos, the photon, the Z boson and the neutral Higgs boson can mix with their corresponding mirror states.² Of particular concern to this paper is photon – mirror photon kinetic mixing,

$$\mathcal{L}_{\text{int}} = -\epsilon F_{\mu\nu} F'^{\mu\nu}, \quad (1)$$

where $F_{\mu\nu}$ ($F'^{\mu\nu}$) is the field strength tensor for ordinary (mirror) electromagnetism, and ϵ is a free parameter. An important experimental consequence of Eq.(1) is the mixing of orthopositronium with mirror orthopositronium [15], leading to oscillations between these states in a vacuum experiment. The subsequent decays of the mirror state are invisible, resulting in an effective increase in the decay rate [15]. A longstanding discrepancy between the theoretical prediction and some of the experimental measurements may in fact be resolved by this mirror world mechanism [16] (see also Ref. [17]). These experiments suggest the value $\epsilon \sim 5 \times 10^{-7}$ which is too large to be palatable for standard BBN [18], but is nevertheless very interesting because of its terrestrially observable consequences.

The purpose of the present work is to consider in detail the physics of the photon – mirror photon mixing. The degeneracy between the ordinary and mirror photons (both of which are assumed to be massless) leads to coherence effects which should be taken into account when considering various processes involving ordinary/mirror photon emission, absorption and scattering. Various interesting astrophysical implications will also be qualitatively discussed. In particular we will find that a small amount of ordinary matter at the center of a mirror star may make the mirror star observable. Indeed such objects may already have been observed, but interpreted as types of white dwarfs.

¹In the EPM the parity symmetry is unbroken by the vacuum, which is one of the reasons it is so simple and predictive. It is also possible to envisage models where the parity symmetry is spontaneously broken [8] which typically have quite different features.

²Other possibilities require physics beyond the minimal model. The most interesting of these would appear to be neutron – mirror neutron and $K_L - K'_L$ mixing (the former requires baryon number violation, while the latter requires flavour changing neutral currents which could occur, for example, in a two Higgs doublet extension).

II. $U(1) \otimes U(1)'$ QUANTUM ELECTRODYNAMICS

Let us consider $U(1) \otimes U(1)'$ quantum electrodynamics containing an ordinary electron ψ and photon A plus a mirror electron ψ' and mirror photon A' ,

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}F'_{\mu\nu}{}^2 + \bar{\psi}(i\hat{\partial} - m)\psi + \bar{\psi}'(i\hat{\partial} - m)\psi' + e\bar{\psi}\hat{A}\psi + e\bar{\psi}'\hat{A}'\psi' - \epsilon F_{\mu\nu}F'^{\mu\nu}. \quad (2)$$

Observe that the last term of the Lagrangian describes the kinetic mixing between the ordinary and mirror photons. This term is gauge invariant and renormalisable and can exist at tree level [6,19], or may be induced radiatively in models without $U(1)$ gauge symmetries (such as grand unified theories) [14,15,20]. Because of kinetic mixing, it turns out that the physical photon is a particular linear combination of A and A' (as will be discussed in the following section). Treating kinetic mixing as a part of the interaction Lagrangian, we obtain the usual Feynman rules plus an extra $A - A'$ mixing vertex shown in Fig. 1a.

To the lowest order in ϵ , the $A - A'$ propagator has the form

$$-i\frac{2\epsilon}{k^2} \left[g_{\mu\nu} - \frac{k_\mu k_\nu}{k^2} \right]. \quad (3)$$

The interaction between the ordinary electron and A' (also to first order in ϵ) takes the form (Fig. 1b):

$$2\epsilon e\gamma^\mu. \quad (4)$$

Similarly, the A field interacts with the mirror electron via the diagram in Fig. 1c.

III. PHYSICAL EFFECTS OF KINETIC MIXING

Clearly one effect of kinetic mixing is to couple mirror electrons to ordinary electrons with an effective charge $2\epsilon e$ [14]. There are also potentially other effects. For example, since the A' field interacts very weakly with ordinary matter one might expect that it could carry energy away from stellar interiors thus speeding up their evolution and, consequently, standard astrophysical arguments would place a strict upper limit on the coupling constant and therefore the mixing parameter ϵ [21].

However, one should take into account the coherence between the emission of the ordinary and mirror photons A and A' . Thus the two diagrams in Figs. 1b and 1d should always be added up coherently. It is convenient to introduce the new field

$$A_1 = \frac{A + 2\epsilon A'}{\sqrt{1 + 4\epsilon^2}}, \quad (5)$$

which can be identified with the *physical photon field*. The orthogonal combination

$$A_2 = \frac{A' - 2\epsilon A}{\sqrt{1 + 4\epsilon^2}}, \quad (6)$$

does not interact with ordinary matter at all. We call A_2 the *sterile photon*.

Thus we see that in the interior of ordinary stars only the physical photon field A_1 is emitted or absorbed and the additional degrees of freedom corresponding to the field A_2 are completely decoupled. Of course, here we assume that the possible admixture of mirror matter in the ordinary stars can be ignored. We therefore conclude that the arguments based on stellar energy loss cannot give us a constraint on the mixing parameter ϵ .

The same arguments as above applied to the mirror star instead of the ordinary one show us that the mirror star would emit the *physical mirror photon*

$$A'_1 = \frac{A' + 2\epsilon A}{\sqrt{1 + 4\epsilon^2}}, \quad (7)$$

whereas the orthogonal field

$$A'_2 = \frac{A - 2\epsilon A'}{\sqrt{1 + 4\epsilon^2}}, \quad (8)$$

will be sterile with respect to mirror matter. We call A'_2 the *sterile mirror photon*. These four states (A_1, A_2, A'_1, A'_2) are summarised in Fig. 2.

Next, let us discuss how one can detect (in principle) the radiation emitted by the mirror star. As explained above, mirror matter will emit the physical mirror photon state A'_1 . To see how the physical mirror photon interacts with ordinary matter, let us rewrite the field A'_1 as a superposition of the physical photon field A_1 and the sterile photon field A_2 :

$$A'_1 = \frac{1 - 4\epsilon^2}{1 + 4\epsilon^2} A_2 + \frac{4\epsilon}{1 + 4\epsilon^2} A_1. \quad (9)$$

If coherence between A_1 and A_2 is maintained, then this superposition couples to ordinary matter with the coupling constant

$$g = \frac{4\epsilon}{1 + 4\epsilon^2} e. \quad (10)$$

While this coherence is preserved in vacuum, and in a medium of purely mirror matter, we will show that in *ordinary* matter it is quickly lost: the state A'_1 actually becomes an incoherent mixture of the sterile photon A_2 and the physical photon A_1 . Because of this decoherence, observationally the radiation from the mirror stars will look like an extremely feeble source of ordinary light rather than like a source of new radiation with a feeble coupling to ordinary matter.

IV. BLOCH-TYPE EQUATION AND DECOHERENCE

In order to describe the decoherence process we introduce the 2×2 reduced density matrix for the states (A_1, A_2) ,

$$\rho = \frac{1}{2}(P_0 + \sigma \cdot \mathbf{P}), \quad (11)$$

where \mathbf{P} , according to common usage, is called “the polarisation vector” (note that this vector is completely different from the “true” polarisation vector describing the photon spin

state). The density matrix is normalised in the standard way: $\text{Tr}\rho = P_0$. For pure quantum states $\text{Tr}\rho^2 = P_0^2$ or, equivalently, $|\mathbf{P}| = P_0$. For all other states $\text{Tr}\rho^2 < P_0^2$ or, equivalently, $|\mathbf{P}| < P_0$. Thus the effect of decoherence (i.e. the transition from a pure state to a mixed state) can be viewed as shortening of the length of the polarisation vector. If the initial wave is described by the pure superposition of Eq.(9), then the corresponding density matrix is

$$\rho(0) = \begin{pmatrix} \left(\frac{4\epsilon}{1+4\epsilon^2}\right)^2 & \frac{4\epsilon(1-4\epsilon^2)}{(1+4\epsilon^2)^2} \\ \frac{4\epsilon(1-4\epsilon^2)}{(1+4\epsilon^2)^2} & \left(\frac{1-4\epsilon^2}{1+4\epsilon^2}\right)^2 \end{pmatrix}, \quad (12)$$

where we have taken $t = 0$ and $P_0(0) = 1$ initially.

Suppose that the initially pure state described by $\rho(0)$ propagates through a medium of ordinary matter. The physical photon component A_1 interacts with the medium, whereas the A_2 component is sterile. This is analogous to an active-sterile two flavour neutrino system propagating through a plasma [22]. The density matrix therefore evolves according to the Bloch-type equation [22]

$$\frac{d\mathbf{P}}{dt} = \mathbf{V} \times \mathbf{P} - D\mathbf{P}_T - a\frac{1}{2}(P_0 + P_z)\hat{z}, \quad \frac{dP_0}{dt} = -a\frac{1}{2}(P_0 + P_z), \quad (13)$$

where \mathbf{P}_T is the projection of the vector \mathbf{P} on the (x, y) -plane. The first term on the right-hand side describes the coherent evolution of the system. It can be viewed as a precession of the vector \mathbf{P} around the direction \mathbf{V} , similar to the precession of a magnetic moment around the direction of a magnetic field. The length of the vector \mathbf{P} is not changed by the precession and therefore the degree of coherence of the initial state is conserved. On the contrary, the second term on the right-hand side of Eq.(13) leads to the contraction of \mathbf{P} and thus also to decoherence. The loss of coherence arises due to collisions with the particles of the medium (opacity, in other words). The third term in Eq.(13) describes the decrease of ordinary light intensity (the magnitude of $P_0 + P_z$) due to absorption.

The components V_x and V_y are given by the off-diagonal elements of the mass matrix and therefore vanish in the basis (A_1, A_2) . So, the Bloch equation simplifies to the coupled system

$$\begin{aligned} \frac{dP_x}{dt} &= -V_z P_y - D P_x, \\ \frac{dP_y}{dt} &= V_z P_x - D P_y, \\ \frac{dP_z}{dt} &= -a\frac{1}{2}(P_0 + P_z), \\ \frac{dP_0}{dt} &= -a\frac{1}{2}(P_0 + P_z), \end{aligned} \quad (14)$$

where V_z is due to coherent forward scattering (refractive index), while D is equal to half of the collision rate of the physical photon with the particles in the medium. Both of these quantities depend on what the ordinary matter composition of the medium actually is.

In any case, the general solution of Eqs.(14) is

$$\begin{aligned}
P_z(t) &= \frac{1}{2}[P_z(0) - 1] + \frac{1}{2}[P_z(0) + 1]e^{-at}, \\
P_x(t) &= e^{-Dt}[P_x(0) \cos V_z t - P_y(0) \sin V_z t], \\
P_y(t) &= e^{-Dt}[P_y(0) \cos V_z t + P_x(0) \sin V_z t], \\
|P_T(t)| &\equiv \sqrt{P_x(t)^2 + P_y(t)^2} = |P_T(0)|e^{-Dt}, \\
P_0(t) &= -\frac{1}{2}[P_z(0) - 1] + \frac{1}{2}[P_z(0) + 1]e^{-at}.
\end{aligned} \tag{15}$$

Decoherence thus forces the density matrix into the diagonal form,

$$\rho = \begin{pmatrix} \left(\frac{4\epsilon}{1+4\epsilon^2}\right)^2 e^{-at} & 0 \\ 0 & \left(\frac{1-4\epsilon^2}{1+4\epsilon^2}\right)^2 \end{pmatrix}, \tag{16}$$

exponentially quickly with characteristic timescale $1/D$. This density matrix describes an incoherent mixture of the ordinary physical photon A_1 and its sterile counterpart A_2 .

Note, however, that if the medium is perfectly transparent to ordinary electromagnetic radiation then there is no decoherence. What happens instead is that oscillations arise because V_z is non-zero due to the refractive index.

V. ASTROPHYSICAL APPLICATIONS

As already discussed in Sec.III, an ordinary star emits just the physical photon field so there is no observable effect of kinetic mixing. Further, Secs.III and IV examined the case of a mirror star, whose mirror photon flux F will produce a flux of order $\epsilon^2 F$ of ordinary light when encountering decohering ordinary matter. Since $\epsilon \lesssim 10^{-6}$ [15,17] this makes them undetectable with present technology unless there happens to be a very luminous mirror star very nearby.

However, there are a number of other physical situations which would be expected to occur given the diversity and size of the universe. In particular, let us consider the following four possibilities

1. Ordinary star with a mirror matter core.
2. Mirror star with an ordinary matter core.
3. Ordinary star with an orbiting mirror planet/star.
4. Mirror star with an orbiting ordinary planet/star.

For the purposes of this paper we will qualitatively identify some of the implications of kinetic mixing. A detailed quantitative study is beyond the scope of the present work, but an interesting topic for the future.

A. Ordinary star with a mirror matter core.

We assume that the mirror matter is confined within a radius $R' < R$, where R is the radius of the star. The embedded mirror matter will be heated up by the interactions with the surrounding ordinary photons. It will lose energy by radiating mirror photons, which will be able to escape if they are emitted near the mirror surface at R' . An equilibrium situation will develop with the mirror matter having some approximate temperature T' at its surface. As the mirror photons propagate out through the star they will, through decoherence, very quickly become sterile photons (with a tiny fraction becoming ordinary photons). They will then rapidly escape from the star, thereby cooling it.

B. Mirror star with an ordinary matter core.

We assume that the ordinary matter is confined within a radius $R < R'$, where R' is the radius of the mirror star. This case is just the mirror image of the previous one, so the dynamics of the system will be the same. However, in this case, the escaping radiation consists of sterile mirror photons (rather than the sterile ordinary photons of the previous case). The sterile mirror photons will become ordinary photons when they interact with ordinary matter (with a tiny fraction becoming sterile ordinary photons) and thus potentially observable by us here on earth! Therefore this case is potentially more interesting than the previous one. There will be several distinctive signatures of this radiation: Its luminosity will be small (depending on R and T) while it can potentially be relatively high in frequency because the surface temperature (i.e. at radius R) of the ordinary matter, T , can be larger than the surface temperature of the mirror star. Thus, such an object would have roughly similar phenomenological characteristics to a type of white dwarf. In fact, there are types of white dwarf (e.g. DC white dwarfs) whose origin is not well understood and may be candidates for mirror stars with some ordinary matter in the centre. Perhaps a good place to look for mirror stars is in the halo of our galaxy. Interestingly, several recent papers [23] claim to have discovered faint moving objects in the halo with an estimated abundance consistent with the MACHO data. The interpretation of these objects as ordinary white dwarfs leads to a number of difficulties [24]. It is therefore tempting to interpret them as mirror stars with a small component of ordinary matter in the centre. This mirror star interpretation can be distinguished from the conventional white dwarf case if the gravitational red shift of the spectral lines can be measured. Light from white dwarfs experience much greater red shift than the light from the center of a typical star. Also note that this type of fake white dwarf could have a mass exceeding the Chandrasekhar limit of 1.4 solar masses: such an object would be a smoking gun for some sort of invisible clumped matter that happens to have acquired an ordinary matter core.

C. Ordinary star with an orbiting mirror planet/star

The ordinary star will emit ordinary photons. Through decoherence, these photons will mostly become sterile mirror photons when they propagate through the mirror planet/star. They will thus travel right through this object making it essentially transparent (only a

tiny component of order ϵ^2 will be absorbed). The sterile mirror photons will then become ordinary photons when they propagate through ordinary matter (which is what all our detection systems are made of). However in a realistic system one might expect the mirror planet/star to have a small amount of ordinary matter embedded into it which might have accreted over time (from e.g. the solar wind). In this case the mirror planet can potentially be opaque, because the small amount of ordinary matter can absorb the ordinary photons from the ordinary star. In the particular case of the large close-in extra-solar planets, this may well be expected because they would accrete a significant amount of ordinary matter from the ordinary star during its lifetime. A detailed study of the optical properties of such an object needs to be done in order to understand the opacity and albedo properties. Obviously any ordinary matter inside the mirror planet will become quite hot and could be a detectable source of ordinary radiation.

D. Mirror star with an orbiting ordinary planet

This system is the mirror image of the previous one. In this case the light from the mirror star may be undetectable, but the ordinary light emitted from the orbiting mirror planet may be observable if such a system is in our neighbourhood and still young. Recently, the detection of “isolated planetary mass objects” has been claimed [25]. In a separate work, we have proposed that these objects might actually not be isolated planets, but rather ordinary planets orbiting invisible mirror stars [26]. This idea can be tested by looking for a periodic Doppler shift in the radiation emitted by the planet.

VI. CONCLUSIONS

The physics of kinetic mixing between ordinary and mirror photons has been elucidated. An important role is played by four linear combinations we have dubbed the physical photon, the sterile photon, the physical mirror photon, and the sterile mirror photon. Because of the mass degeneracy between the two gauge bosons, quantum coherence effects have to be carefully considered. In particular, the physical photon becomes a certain coherent superposition of the bare ordinary photon and the bare mirror photon. Similarly, the physical mirror photon is another, but *not orthogonal*, coherent superposition of the bare states. By using a Bloch equation analysis, we have shown that physical mirror photons decohere into a mixture of physical (ordinary) photons and sterile photons when they propagate through ordinary matter. The relative proportions are determined by the (necessarily small) kinetic mixing parameter ϵ . Since all our detection apparatus is composed of ordinary matter, this implies that a mirror star will appear to be a very weak source of ordinary photons rather than a bright source of new radiation which couples very weakly to ordinary matter.

Observational signatures of some hybrid ordinary/mirror binary astrophysical systems were qualitatively discussed. A mirror star with an ordinary matter core can phenomenologically mimic a white dwarf, and we have speculated that badly understood objects such as DC white dwarfs might actually be such hybrids.

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VII. FIGURE CAPTIONS

Figure 1: a) $A - A'$ mixing vertex. b) The interaction between the ordinary electron and A' . c) The interaction between the mirror electron and A . d) The interaction between the ordinary electron and A .

Figure 2: Representation of the photon/mirror photon states. Because A and A' are degenerate (both massless) any point on the circle is a possible physical state in vacuum. For propagation in ordinary matter the degeneracy is lifted, with the states A_1 (the photon) and A_2 (the orthogonal "sterile photon" state) being the Hamiltonian eigenstates. A_2 and A'_2 are the corresponding mirror states for propagation in mirror matter. Note that $\tan \theta = \epsilon$.

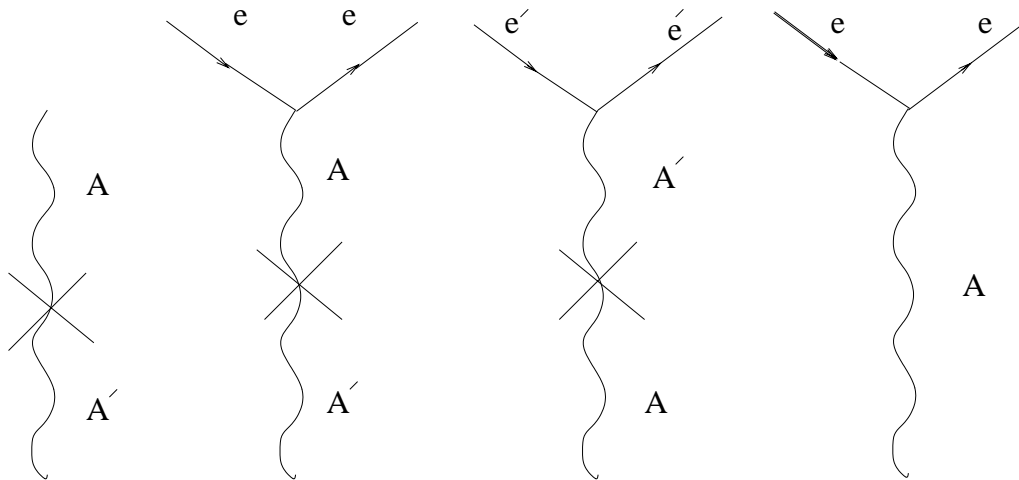


Figure 1a,b,c,d

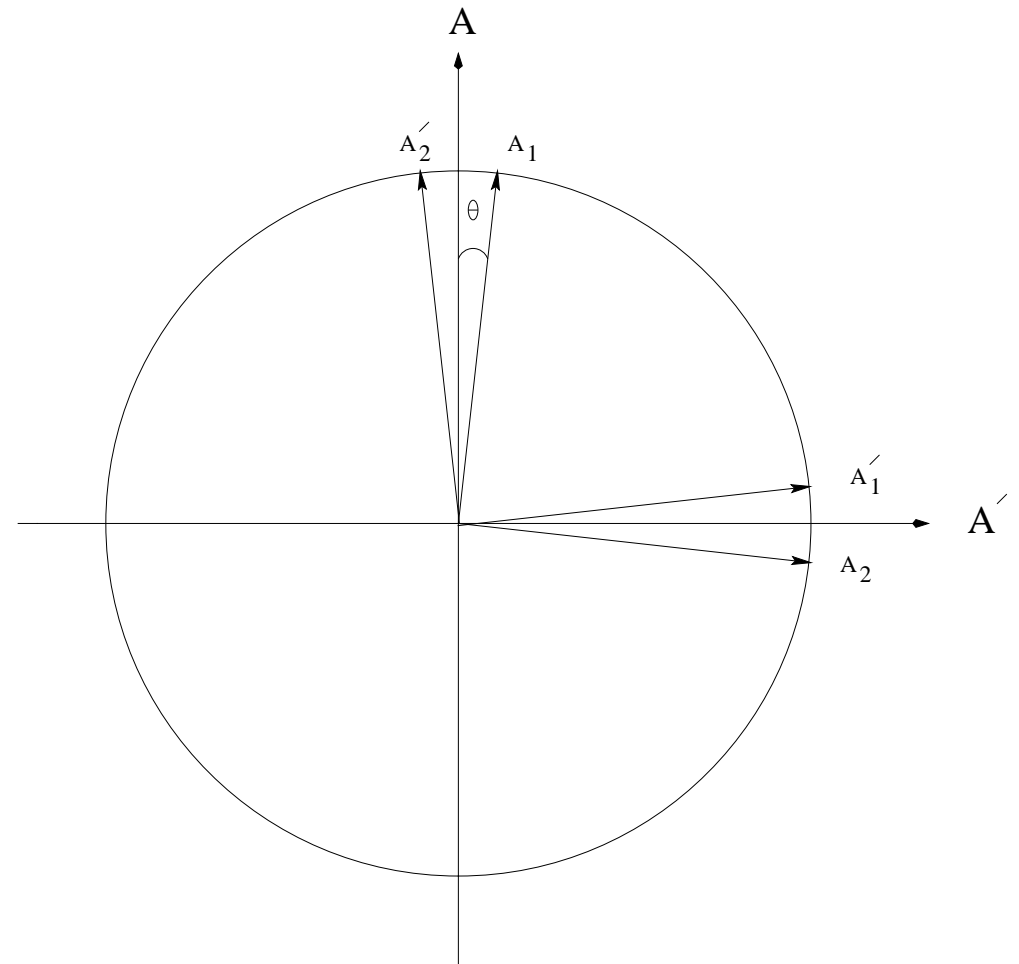


Figure 2